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Ian Baker

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14. ABSTRACT
The goal of this project was to characterize the structural evolution of dry snow as it underwent metamorphism under either quasi-isothermal conditions or a temperature gradient, and to determine the dominant mass transport mechanism. Observational techniques involved a combination of optical microscopy, scanning electron microscopy (SEM) and X-ray computed microtomography (micro-CT). Because of its non-destructive nature, the micro-CT enabled the collection of time-series images, including the acquisition of various quantified structural parameters as

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Report Title

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The goal of this project was to characterize the structural evolution of dry snow as it underwent metamorphism under either quasi-isothermal conditions or a temperature gradient, and to determine the dominant mass transport mechanism. Observational techniques involved a combination of optical microscopy, scanning electron microscopy (SEM) and X-ray computed microtomography (micro-CT). Because of its non-destructive nature, the micro-CT enabled the collection of time-series images, including the acquisition of various quantified structural parameters as porosity and specific surface area. Fine structural features and impurities in both fresh and metamorphosed snow were examined using the SEM. In addition, ice sphere arrays were studied as geometrically-simplified aggregates and it was found that while small protrusions grew to bridge the gap between adjacent ice spheres under a quasi-isothermal condition, a larger number of faceted crystals developed under a temperature gradient >100°C/m.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

“Investigation on the sintering process of dry snow”, S. Chen, R. W. Lomonaco and I. Baker, poster at the Workshop on the Microstructure and Properties of Firn, Dartmouth College, NH, March 10-11th, 2008.

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Number of Presentations: 17.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

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Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

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Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

02/18/2011 3.00 S. Chen, I. Baker. The Influence of Temperature Gradient on Sintering of Ice Particles, (02 2011)

02/18/2011 4.00 R. Lomonaco, I. Baker, S. Chen. Preliminary Results on the Characterization of Firn Using SEM and Micro CT, (02 2011)

02/18/2011 6.00 S. Chen, I. Baker. In-situ Observations of Snow Sublimation using Scanning Electron Microscopy , (02 2011)

TOTAL: 3

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

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Si Chen and Ian Baker won 1st Place, Class 4 Electron Microscopy - Scanning at the 2009 International Metallographic Contest for a poster entitled “In-Situ Observations of Snow Microstructural Evolution”.

Ian Baker became a Fellow of the Materials Research Society in 2011.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Si Chen	1.00	
FTE Equivalent:	**1.00**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Ian Baker	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Total Number:	

Names of personnel receiving PHDs

NAME	
Si Chen (1)	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment.

Technology Transfer

Dry Snow Metamorphism
Final Report
Grant: 51065-EV

Ian Baker
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Goals

The goal of this project was to characterize snow as it undergoes metamorphism, to understand the mass transfer mechanisms, and to develop a model for this behavior.

Objectives

The primary objectives of this investigation were:

1. Use laboratory-produced ice spheres to characterize the formation of necks between adjacent ice crystals.
2. Explore the effect of a temperature gradient on the sintering of ice crystals.
3. Collect and store natural snow for observing the structural evolution and the changes in structural parameters, including relative density, specific surface area, structure thickness, structure separation, structural model index, and degree of anisotropy.
4. Use a cold stage-equipped scanning electron microscope (SEM) and an X-ray computed microtomography scanner (micro-CT) to obtain high-resolution images and three-dimensional (3-D) models of snow specimens at different stages of metamorphism.
5. Describe and analyze the behavior of snow during metamorphism and grain sintering using mathematical models.

Approach

Our approach involved the collection and storage of fresh snow, the production of ice spheres as a simplified and more basic model of the contact area between two grains of snow, and the examination of both types of specimens at various stages of metamorphism using the SEM and micro-CT. More specifically, the above approach involved the following tasks:

1. Collection and storage of natural snow from Hanover, NH - We collected fresh snow during snow events in Hanover, and stored the samples under different thermal conditions.
2. Production of ice sphere arrays - We produced small ice spheres (~4 mm dia.) by dropping water into liquid nitrogen. The frozen water drops were picked up using a sieve and arranged in specially constructed sample holders to form 1-D, 2-D, and 3-D arrays.
3. Optical inspection of snowflakes and ice spheres with transmitted light - Using an optical microscope, we characterized the change of crystal size and geometry with emphasis being placed on characterizing the size and shape of bonds between crystals.
4. Effects of temperature gradient on ice sphere sintering and snow metamorphism - We built a temperature-controlled system in a cold room and set up different temperature gradients across ice sphere arrays and natural snow specimens. We performed periodic observations primarily using the micro-CT to track the structural changes of specimens.
5. SEM for high-resolution images - We characterized the microstructures of ice spheres, fresh snow, and sintered snow using a cold stage-equipped SEM and detect elements using energy dispersive X-ray microanalysis (EDS).
6. Micro-CT to produce 3-D models and to monitor structural parameters - We obtained time-series 3-D images of ice particles, fresh snow, sintered snow, and natural firn in order to examine the changes in the internal structural over time. We monitored the structural parameters, such as density, specific surface area, and degree of anisotropy, in order to quantify the structural evolution.

7. Model the behavior of both ice spheres and natural snow under quasi-isothermal conditions – We analyzed the stability of the surface of ice spheres subjected to quasi-isothermal conditions. We calculated the growth exponent in the coarsening theory based on the computed structural parameters in order to further quantify the behavior of snow aggregates.

Tasks Completed

The following tasks were completed:

1. Fresh snow was collected and stored for observation.
2. Ice spheres were produced in a cold room from both de-ionized water and sulfuric acid-doped water. The structural evolution of each type was studied using both an optical microscope and the SEM.
3. The stability of the surface of ice spheres maintained at quasi-isothermal conditions was analyzed using the mathematic model proposed by Mullins and Sekerka (1963).
4. A temperature-gradient cell was built in order to study kinetic metamorphism (metamorphism under a high temperature gradient, usually larger than $10^{\circ}C \cdot m^{-1}$).
5. High-resolution images and X-ray spectra of snow specimens at various metamorphism stages were obtained using an SEM and EDS.
6. The results from micro-CT were validated through combining the use of SEM and micro-CT.
7. The structural evolution of natural snow under different thermal conditions was observed using the micro-CT, quantified by monitoring the changes in structural parameters, and analyzed using coarsening theories.
8. The structural evolution of ice sphere arrays under different thermal condition was observed using the micro-CT.

Results

Observation of the sintering process of lab-produced ice spheres.

1. We produced ice spheres (~4 mm dia.) in a cold room, by dropping water into liquid nitrogen. The frozen spheres were picked up using a sieve and arranged in specially constructed sample holder to form 1-D, 2-D, and 3-D ice sphere arrays.
2. We recorded the sintering process of ice spheres (made from de-ionized water) under a quasi-isothermal condition (-10 ± 0.5ºC). The spheres were made and stored in a cold room at -10ºC. Necks with high porosity formed between two ice spheres shortly after they were laid in contact. Over a period of one month, the necks tended to densify by filling up the pores with water molecules. Figure 1 shows optical images obtained at different time intervals. Small protrusions on the surface of ice spheres had a preferred growth direction from one ice sphere towards an adjacent one (Figure 2).
3. We recorded the sintering process of ice spheres under a high temperature gradient (500°C/m). In a couple of hours, highly-faceted crystal (Figure 3) growth was observed around necks, whose normal direction was parallel to the vapor flow in the ice sphere array.
4. We obtained high-resolution images of microstructures using the SEM. Figure 4 shows the microstructures of the neck between two ice spheres, including grain boundaries and the curvature of the neck.
5. W obtained time-series 3-D images of 1-D ice sphere arrays, which were maintained under isothermal conditions, using the micro-CT (Figures 5 and 6). Secondary electron images of the neck areas showing that small ice protrusions grew from one ice sphere to the adjacent one (Figures 7 and 8). Filaments were observed on the upper surface of ice spheres (Figure 9), suggesting mass sublimation.
6. We obtained time-series 3-D images of 1-D ice sphere arrays, which were subjected to a temperature gradient, using the micro-CT (Figures 10 and 11). Secondary electron images of the cross-section through the neck area showing the development of hoar structure crystals close to the surface of the ice sphere (Figure 12) and the formation of pores inside the neck (Figures 12 and 13).

7. We obtained secondary electron images of vertical cross-sections (Figure 14) showing the development of structural alignment along the temperature gradient.
8. We obtained time-series images of a 3-D ice sphere array maintained at -2.3±0.2°C using the micro-CT (Figure 15). Secondary electron images (Figure 16) show the small protrusions and small protrusions developed on the surface of ice spheres,. Similar phenomenon was also observed in 1-D ice sphere arrays under quasi-isothermal conditions.
9. We obtained time-series images of a 3-D ice sphere array, which was subjected to a temperature gradient, using the micro-CT (Figure 17). Both the vertical and horizontal cross sectional images through the specimen were obtained using the micro-CT (Figures 18 and 19), showing the development of vertical structural alignment and hoar structure crystals, respectively.
10. We analyzed the stability of the surface of ice spheres under quasi-isothermal conditions using the approach that was proposed for analyzing the stability of a moving interface during solidification by Mullins and Sekerka (1963).
11. We analyzed the possible complexity induced by using the ice spheres produced by freezing water droplets in liquid nitrogen.

Observation of Antarctic firn.

1. We observed firn specimens using the SEM. Figure 20 shows the microstructures of two specimens. One specimen was observed at -150°C, with negligible sublimation. The other specimen was thermally etched at -60°C and underwent substantial sublimation, resulting in the formation of filament webs on the surface. The elements present in the filaments were determined using EDS (Figure 21).
2. We developed 3-D images of firn using the micro-CT.
3. We validated the data from micro-CT by comparing the images obtained from micro-CT to the ones obtained using the SEM. We produced a mosaic SEM image of a certain cross-section and found the corresponding cross-section image in the micro-CT data set (Figure 22). This also allowed us to select the best binarization threshold for future micro-CT analysis of these specimens.

Observation the morphology and structural evolution of natural snow over time.

1. We observed fresh snow using the SEM. Figure 23 shows the morphology of a fresh-snow specimen as an example. Figure 24 shows snowflakes of various geometries found in this specimen.
2. We observed the sublimation process of a snowflake in the SEM. We slowly warmed the specimen up from -180°C to -100°C to initiate mass sublimation. By continuously taking images over a period of 25 minutes and recording the temperatures and times, we monitored the geometry changes (Figure 25).
3. We recorded the structural evolution of natural snow under quasi-isothermal conditions using the micro-CT. We developed 3-D images and monitored the evolution of structural parameters, such as density, specific surface area, and degree of anisotropy. An example of quasi-isothermal evolutions is shown in Figures 26 and 27. The specimen was maintained at -5°C. The structural parameters were obtained using different threshold values in order to demonstrate the threshold sensitivity of the evaluation using the micro-CT.
4. The structural evolution under an isothermal condition was analyzed using coarsening theory. The growth exponent in the coarsening theory was calculated from the fitting curve of the measurements and primarily used for performing comparisons of different snow specimens.
5. We tracked the changes in single snowflakes in a snow aggregate as they evolved over time using the micro-CT. We scanned snow aggregate in the micro-CT and extracted images for single snowflakes during image processing. An example is shown in Figure 28.
6. We recorded the structural evolution of natural snow subjected to a temperature gradient. An example is shown in Figure 29. Time-series images obtained using the micro-CT showing the process of crystal coarsening over time. Snow crystals randomly selected from the specimen undergoing kinetic metamorphism were examined using the SEM. Faceted crystals were observed with raised steps on the edges and newly-developed ice layers on the surface (Figure 30), which could be the early stage of hoar structure formation. Vertical crystal chains also developed

under a temperature gradient and are displayed using the images of three orthogonal planes (Figure 31).

7. The evolutions of structural parameters were compared between specimens with different initial density or under different thermal conditions.

Technology Transfer

1. We worked with General Mills and examined Haagen-Dazs ice cream using the SEM and micro-CT to determine porosity and fat droplet distribution.

2. The cryotransfer/cold stage SEM and preparation facilities that the PI has established at Dartmouth have become of use to others: Prof. Ian Nettleship of the U. Pittsburgh and Prof. Ulrike Wegst at Drexel University have separately used them to examine ice/alumina composites that are grown for biomedical applications (the ice is subsequently sublimed away to leave an alumina scaffold); and Prof. David Goldsby of Brown University and his collaborator Dr. Dave Prior of the University of Liverpool, U.K. have used the facility to look at ice specimens after creep studies. Finally, Prof. W. Durham of M.I.T. has collaborated with us to use the SEM/EBSP setup to look at very fine grained ice. The P.I. is studying ice and firn cores from Greenland and Antarctica under NSF funding using both these methods and a recently-acquired, coldroom-adapted micro CT in NSF projects entitled “Collaborative Research: The NEEM Deep Ice Core”, “Advanced Microstructural Characterization of Polar Ice Cores”, “IGERT: Polar Environmental Change” (P.I. R. Virginia) and Firn Metamorphism: Microstructure and Mechanisms (P.I. – M. Albert, Co-P.I. I. Baker).

Publications

"Effects of Impurities and their Redistribution during Recrystallization of Ice Crystals", D. Iliescu and I. Baker, Journal of Glaciology, **54** (2008) 362-370(9).

On the Effects of Temperature on the Strength of H_2SO_4-Doped Ice Single Crystals", X. Li, D. Iliescu and I. Baker, Journal of Glaciology, **55** (2009) 481-484.

"The Influence of Temperature Gradient on Sintering of Ice Particles", S. Chen and I. Baker, 65th Eastern Snow Conference, Fairlee (Lake Morey), VT, May 28-30th, 2008, p293-300.

"Preliminary Results on the Characterization of Firn Using SEM and Micro CT", R.W. Lomonaco, I. Baker, and S. Chen, 65th Eastern Snow Conference, Fairlee (Lake Morey), VT, May 28-30th, 2008, p359-364.

"Firn", Rachel W. Obbard, Ian Baker and Rachel W. Lomonaco, Encyclopedia of Snow, Ice and Glaciers, V. Singh, P. Singh, and U. K. Haritashya (eds.), Springer, ISBN: 978-90-481-2643-9, 2011. **INVITED**

"*In-situ* Observations of Snow Sublimation using Scanning Electron Microscopy", S. Chen and I. Baker, proceeding of the 66th Annual Eastern Snow Conference, 9–11th June 2009, Niagara-on-the Lake, Ontario, Canada, p5-9. (*Weisnet Medal for Best Student Paper*)

"Structural Evolution during Ice-sphere Sintering", S. Chen and I. Baker, 2010, Hydrological Process, **24**(14), 2034-2040, DOI: 10.1002/hyp.7787.

"Observation of the Morphology and Sublimation-induced Changes in Uncoated Snow using SEM", S. Chen and I. Baker, 2010, Hydrological Process, **24**(14), 2041-2044, DOI: 10.1002/hyp.7787.

"The Evolution of Individual Snowflakes during Metamorphism", S. Chen and I. Baker, 2010, Journal of Geophysical Research, **115**, D21114, DOI: 10.1029/2010JD014132.

A Cryo-SEM image published as the cover image of Journal of Glaciology, **56**(197), 2010.

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Personnel Supported

Si Chen – Ph.D. student

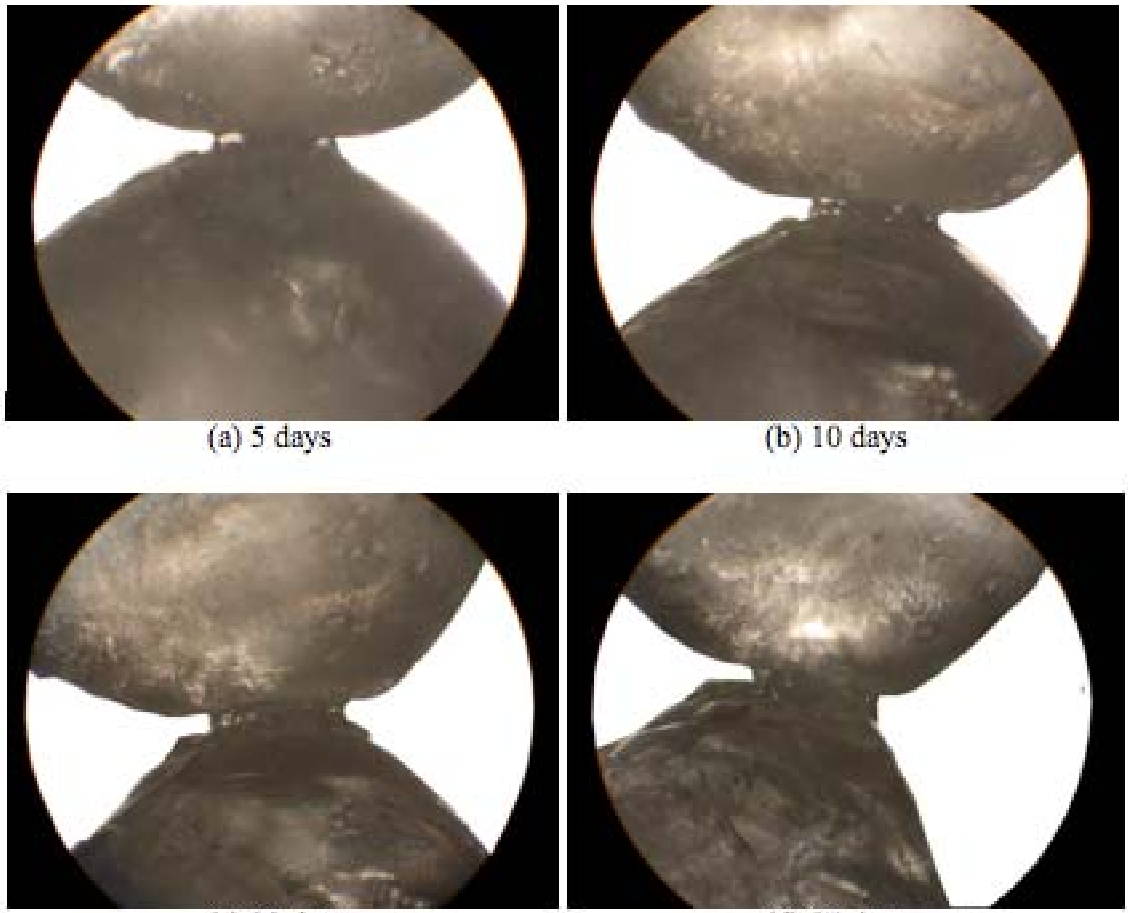


Figure 1. Showing the sintering process between two ice spheres. The ice spheres were made of high-purity water and stored in cold room around -5°C.

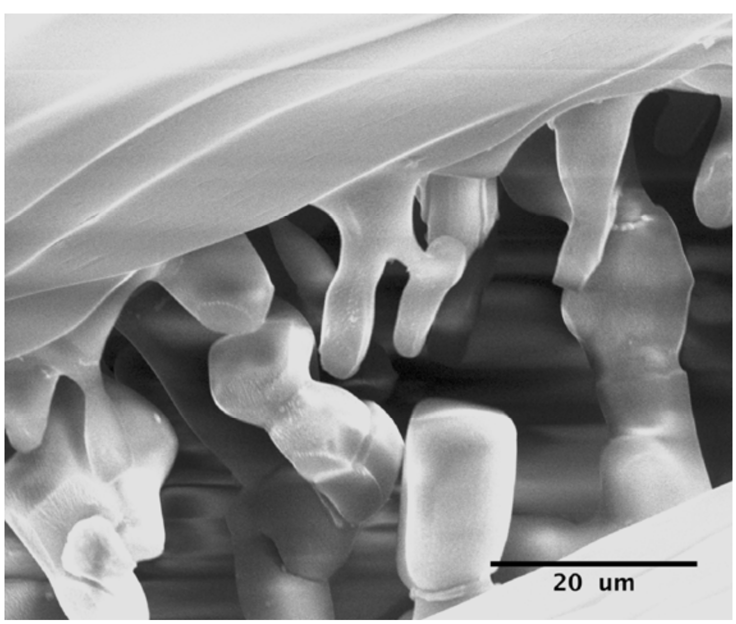


Figure 2. Secondary electron image showing the growth of ice particles from one ice sphere towards an adjacent one.

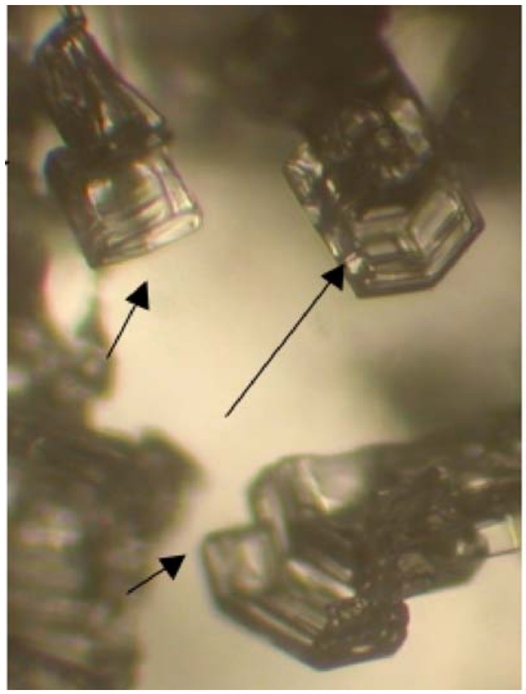
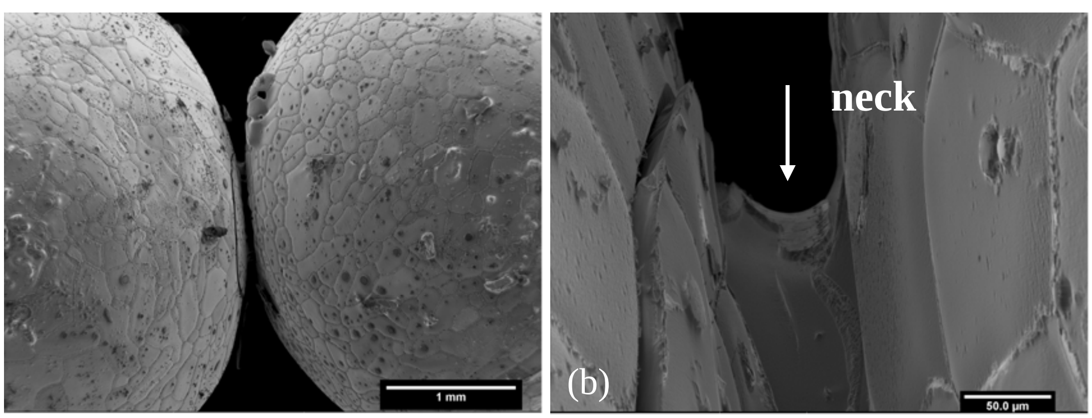


Figure 3. Optical image of faceted ice crystals grown around necks between ice spheres under a high temperature gradient.



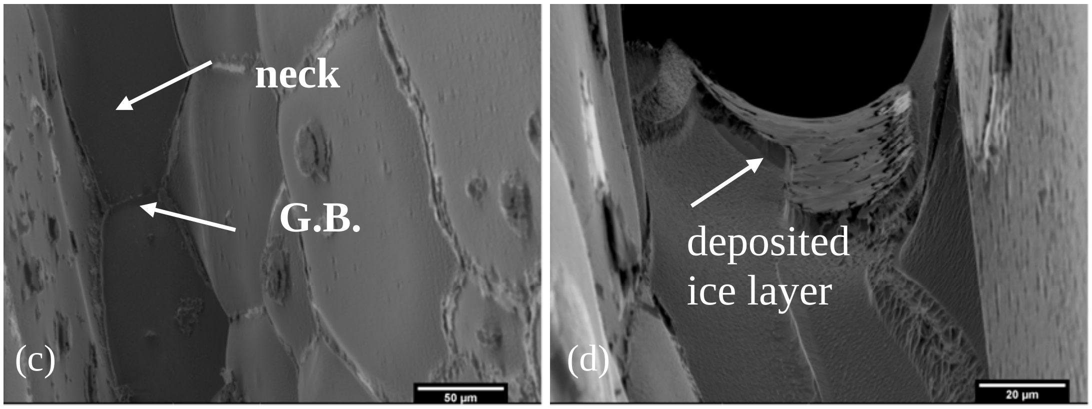


Figure 4. Secondary electron images of the neck between two ice spheres, showing the grain boundaries in the neck and curvature on the edge.

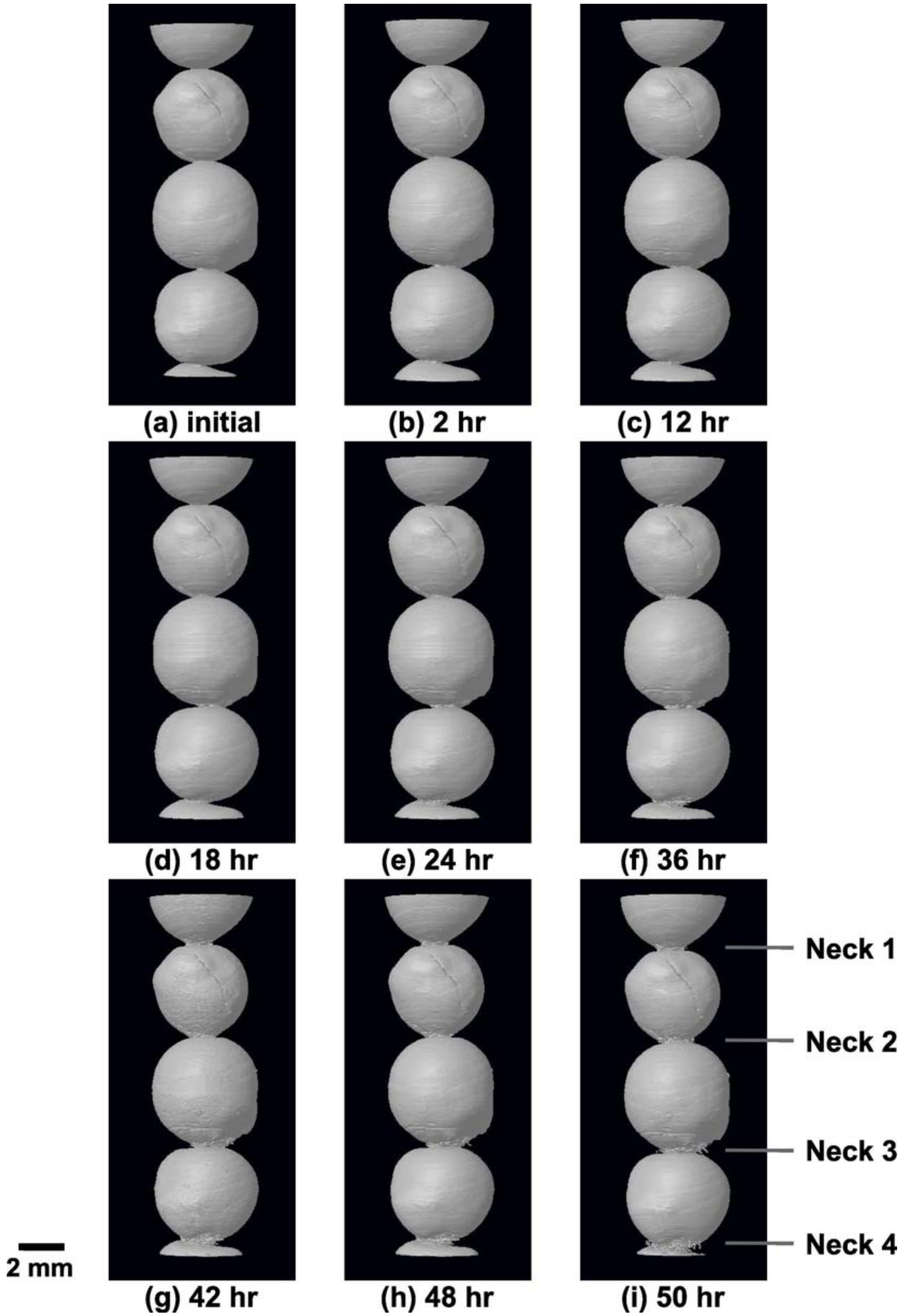


Figure 5. 3-D micro-CT images showing the structural changes of a 1-D ice sphere array maintained at -2.3±0.2°C for 50 hours. The images were acquired using a 15 µm image pixel size.

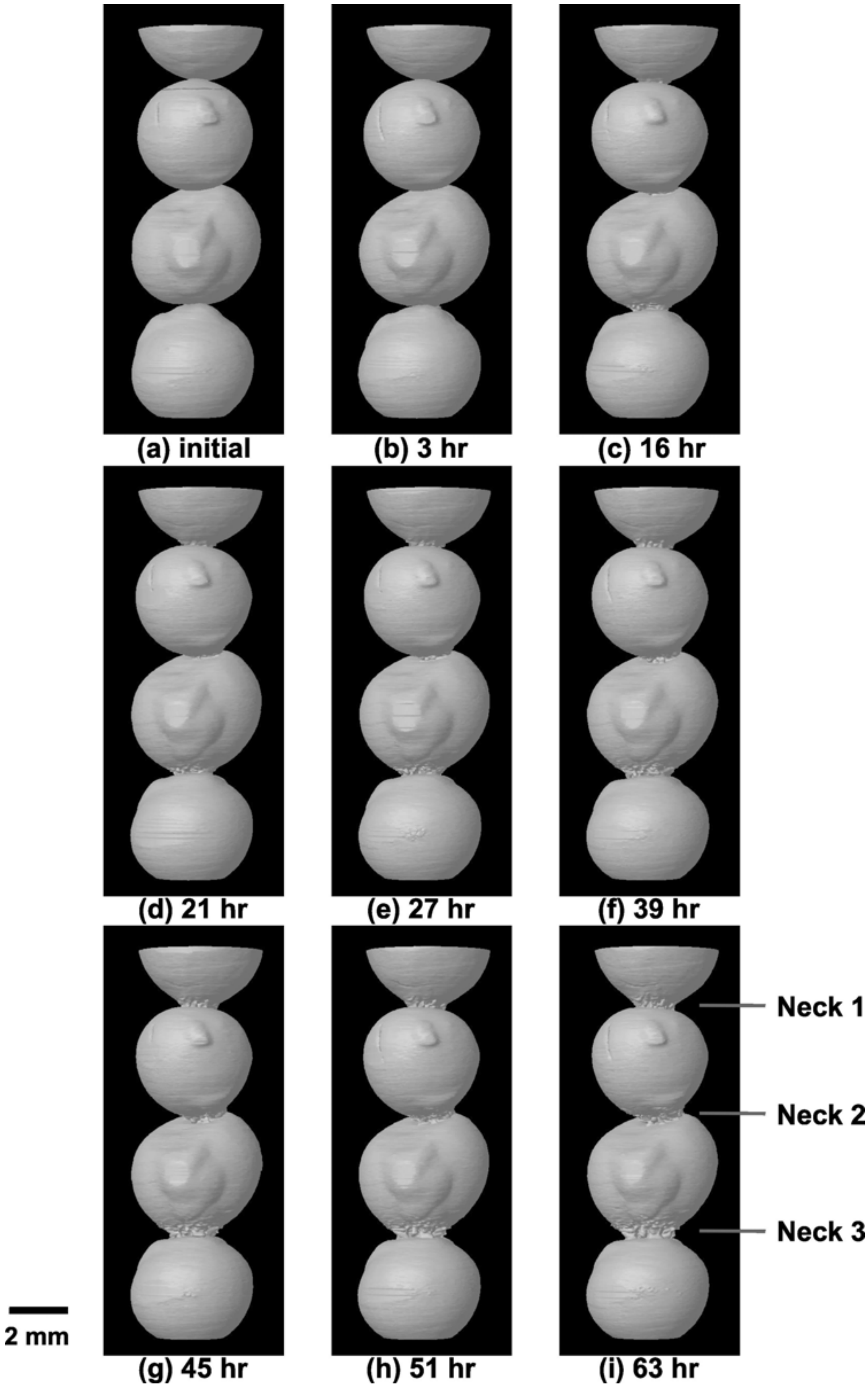


Figure 6. 3-D micro-CT images showing the structural changes of a 1-D ice sphere array maintained at -10±0.2°C for 63 hours. The images were acquired using a 15 µm image pixel size.

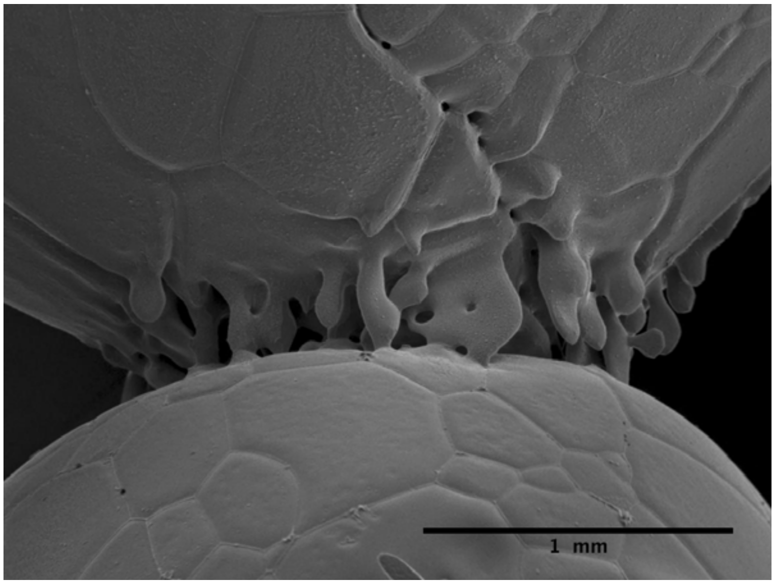


Figure 7. Secondary electron image of Neck 4 in Figure 5 showing the development of ice crystals on the bottom of the ice sphere and grew downwards.

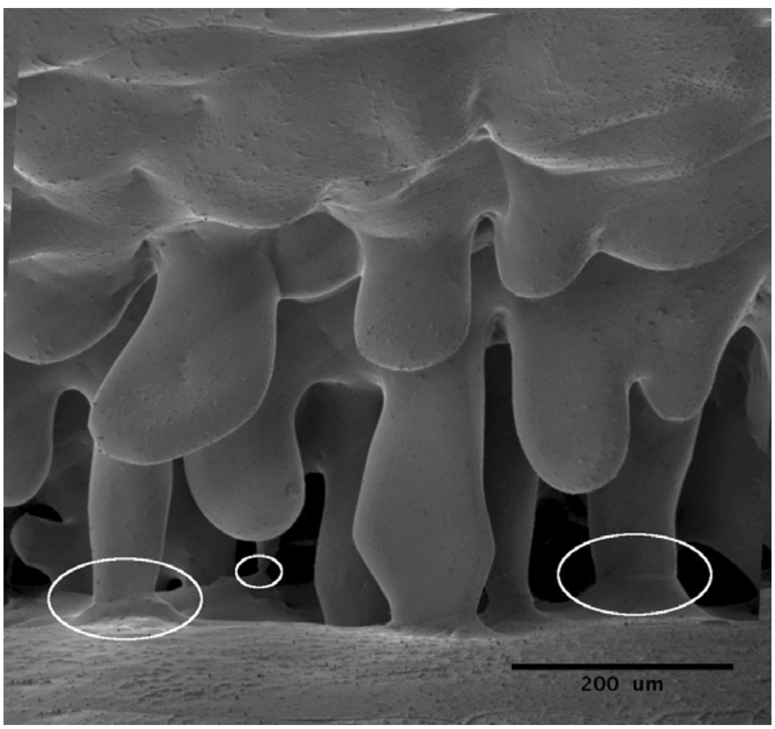


Figure 8. Secondary electron image showing grain boundaries between the protrusions and the lower ice sphere.

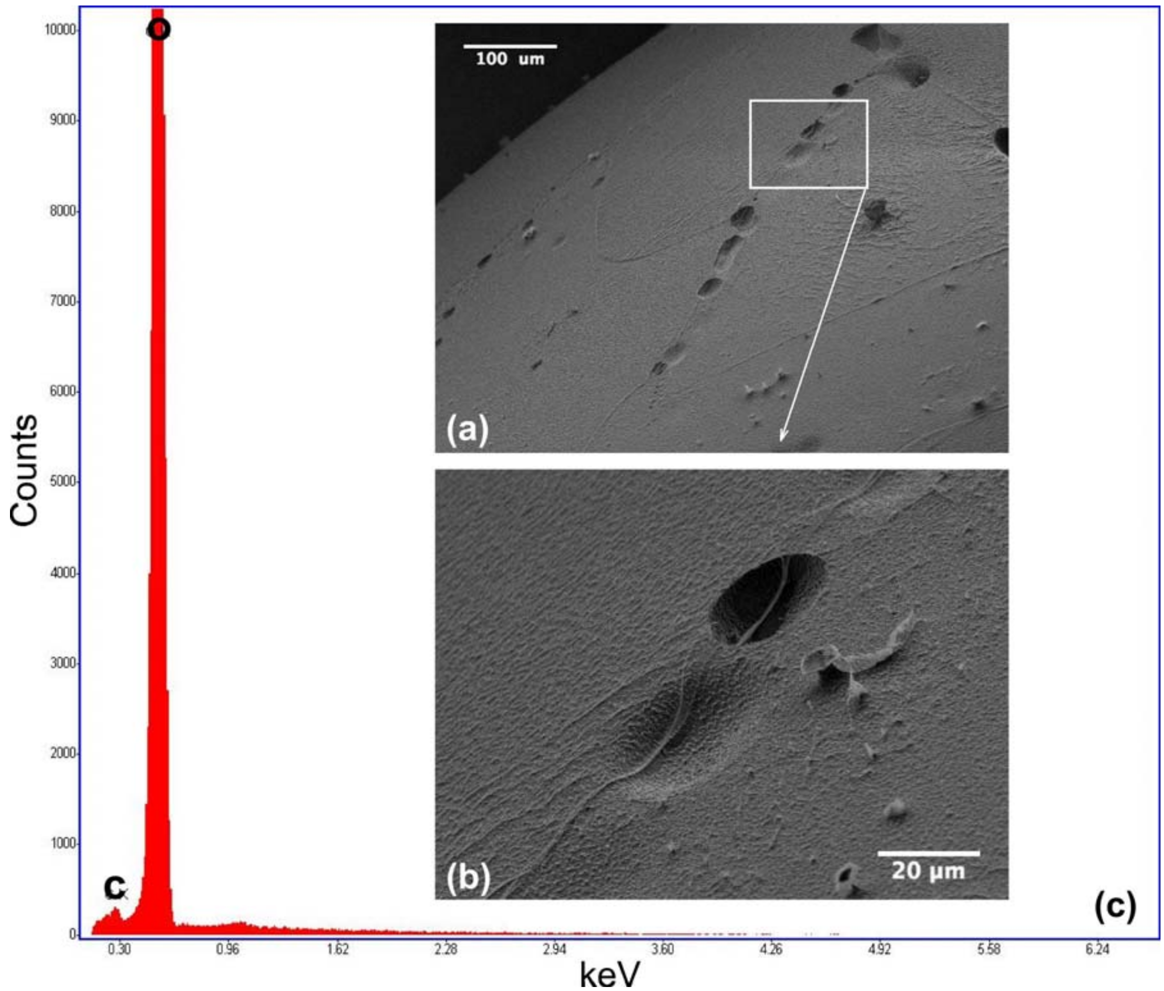


Figure 9: Secondary electron images showing the morphology of the upper surface of an ice sphere in the array shown in Figure 6 after 63 hours: (a) concave areas were observed developing on the surface, frequently along grain boundaries; (b) filaments developed across the concave areas; and (c) an EDS spectrum collected from the filament indicates a small amount of carbon.

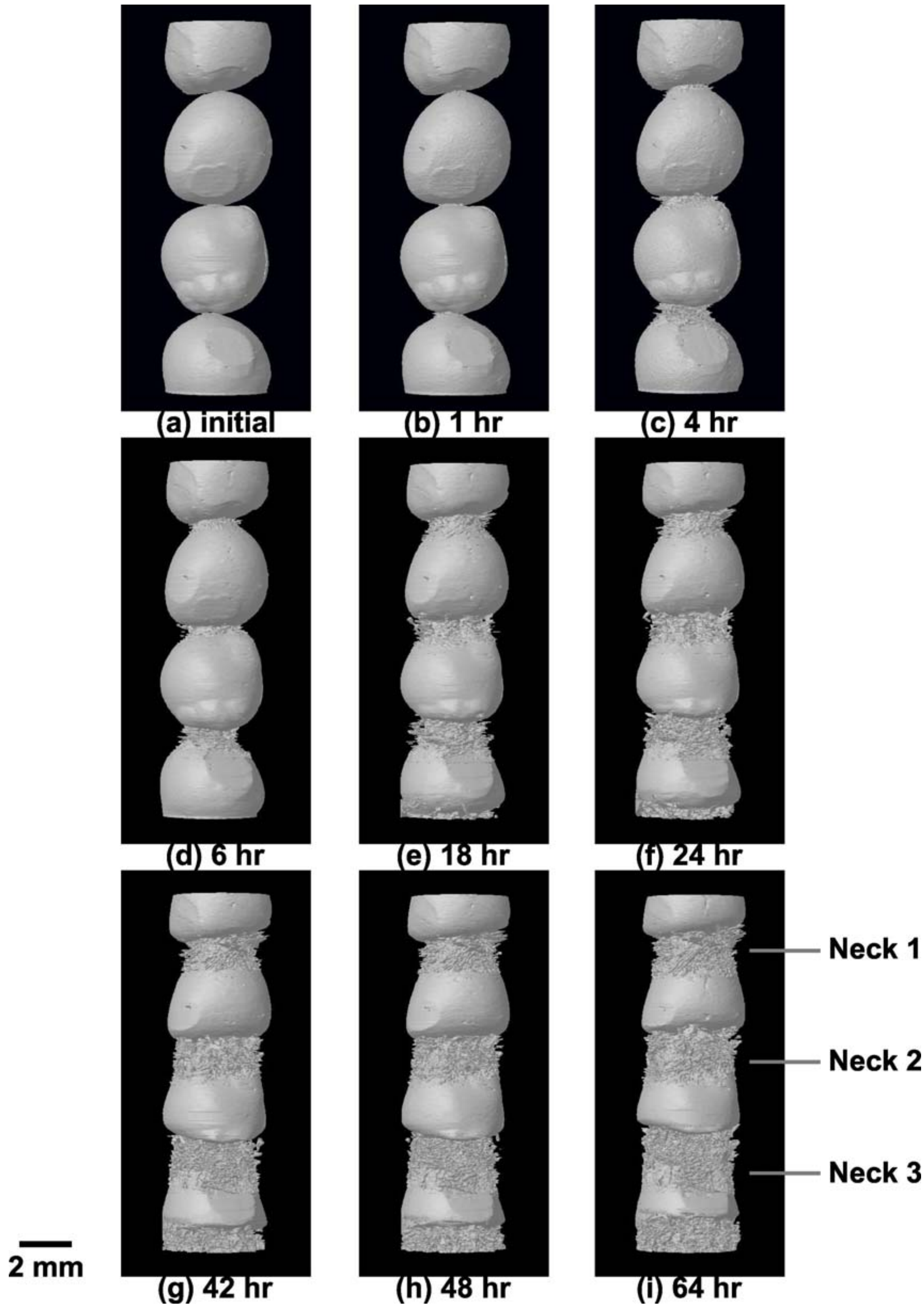


Figure 10. 3-D micro-CT images showing the structural changes of a 1-D ice sphere array under a temperature gradient of 135°C·m^{-1} for 64 hours. The images were acquired using a 15 µm image pixel size.

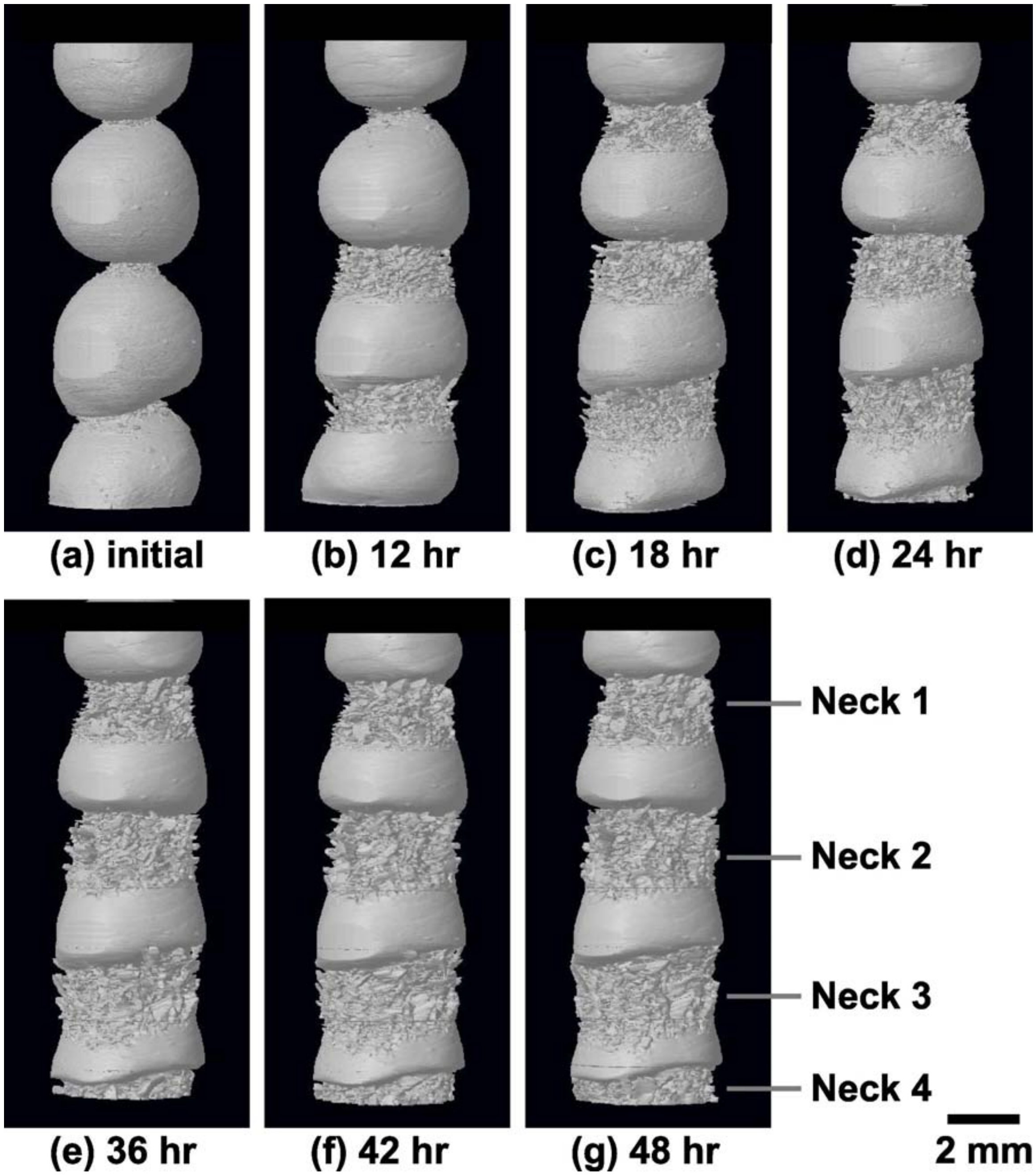


Figure 11. 3-D micro-CT images showing the structural changes of a 1-D ice sphere array under a temperature gradient of 385°C·m^{-1} for 48 hours. The images were acquired using a 15 µm image pixel size.

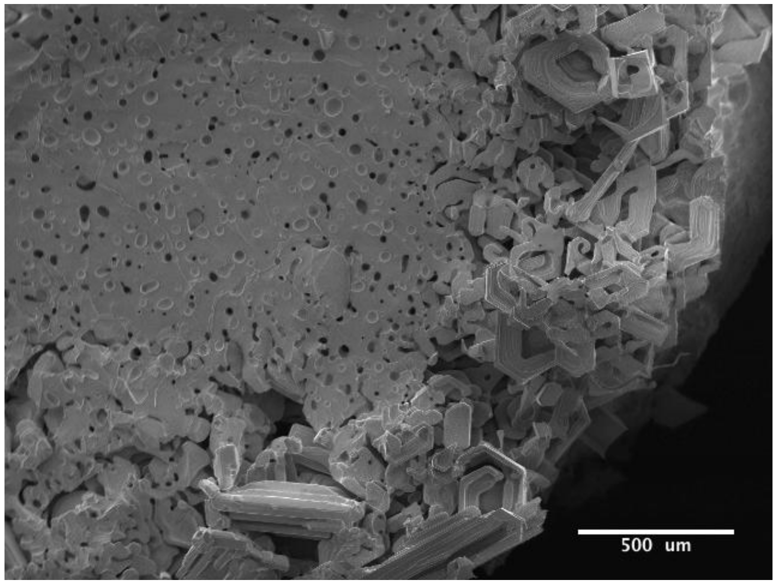


Figure 12. Secondary electron image of a cross-section through Neck 4 in Figure 11 showing hoar structure crystals on the surface and the pores inside.

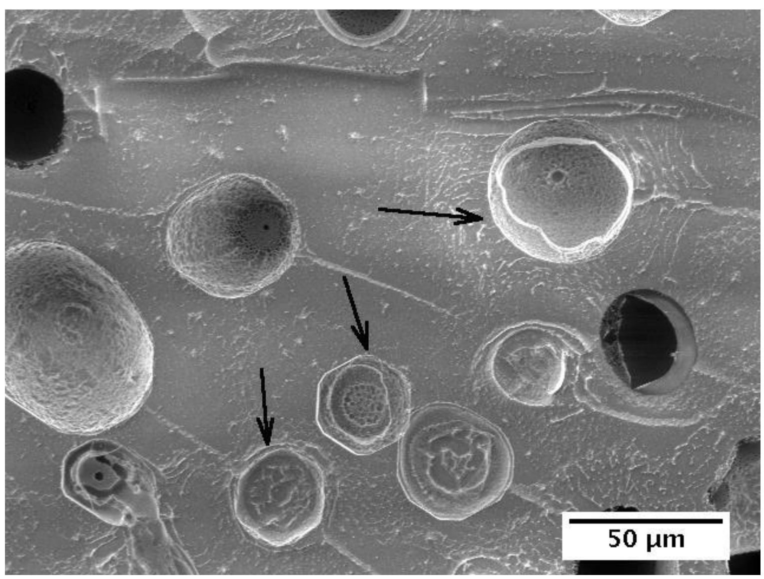


Figure 13. Secondary electron image of a cross-section of a neck between two ice spheres showing shallow, circular or hexagonal depressions with patterns on the interfaces.

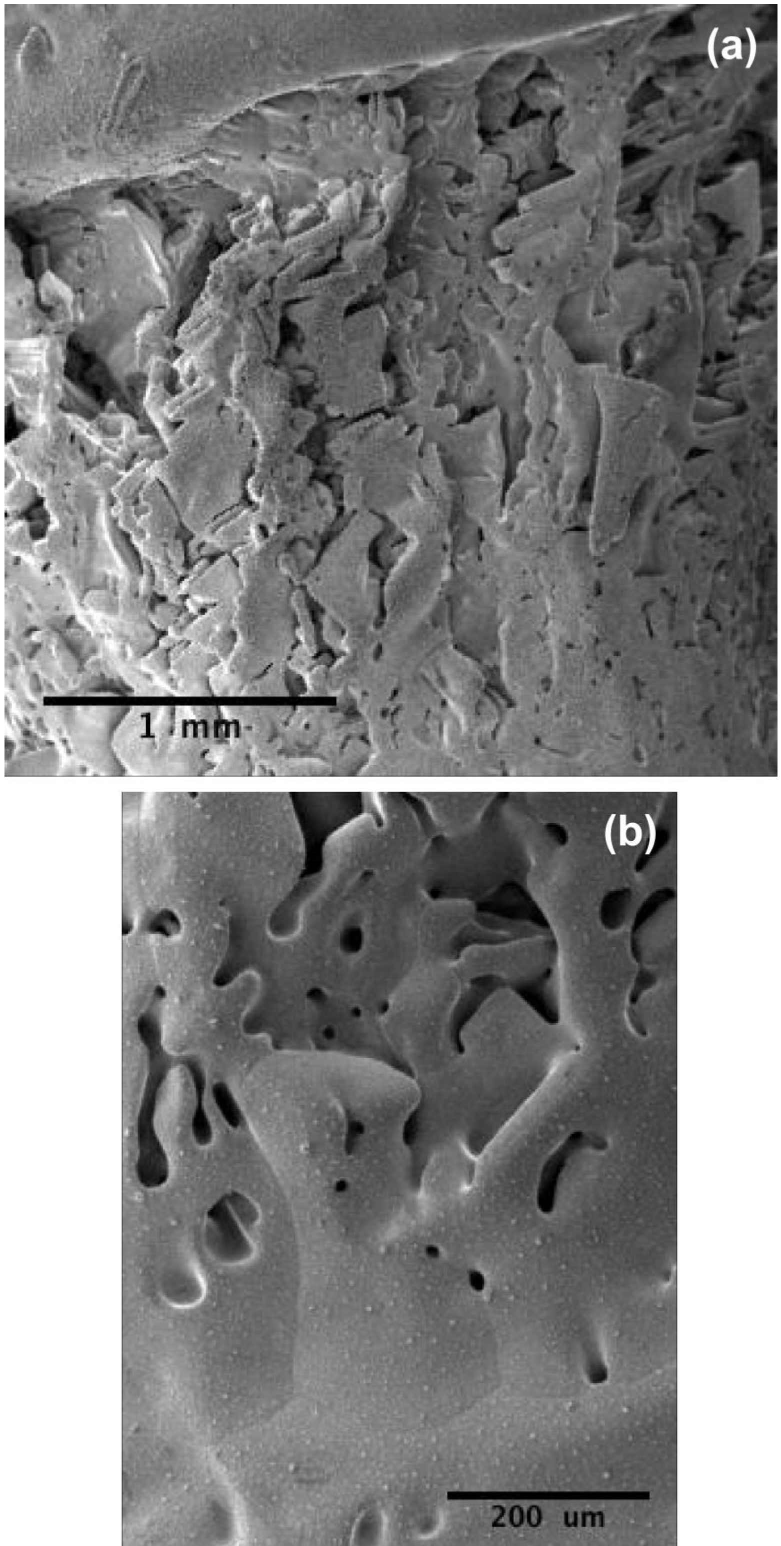


Figure 14. Secondary electron image of Neck 4 as indicated in Figure 11, showing the development of vertically aligned ice crystal chains.

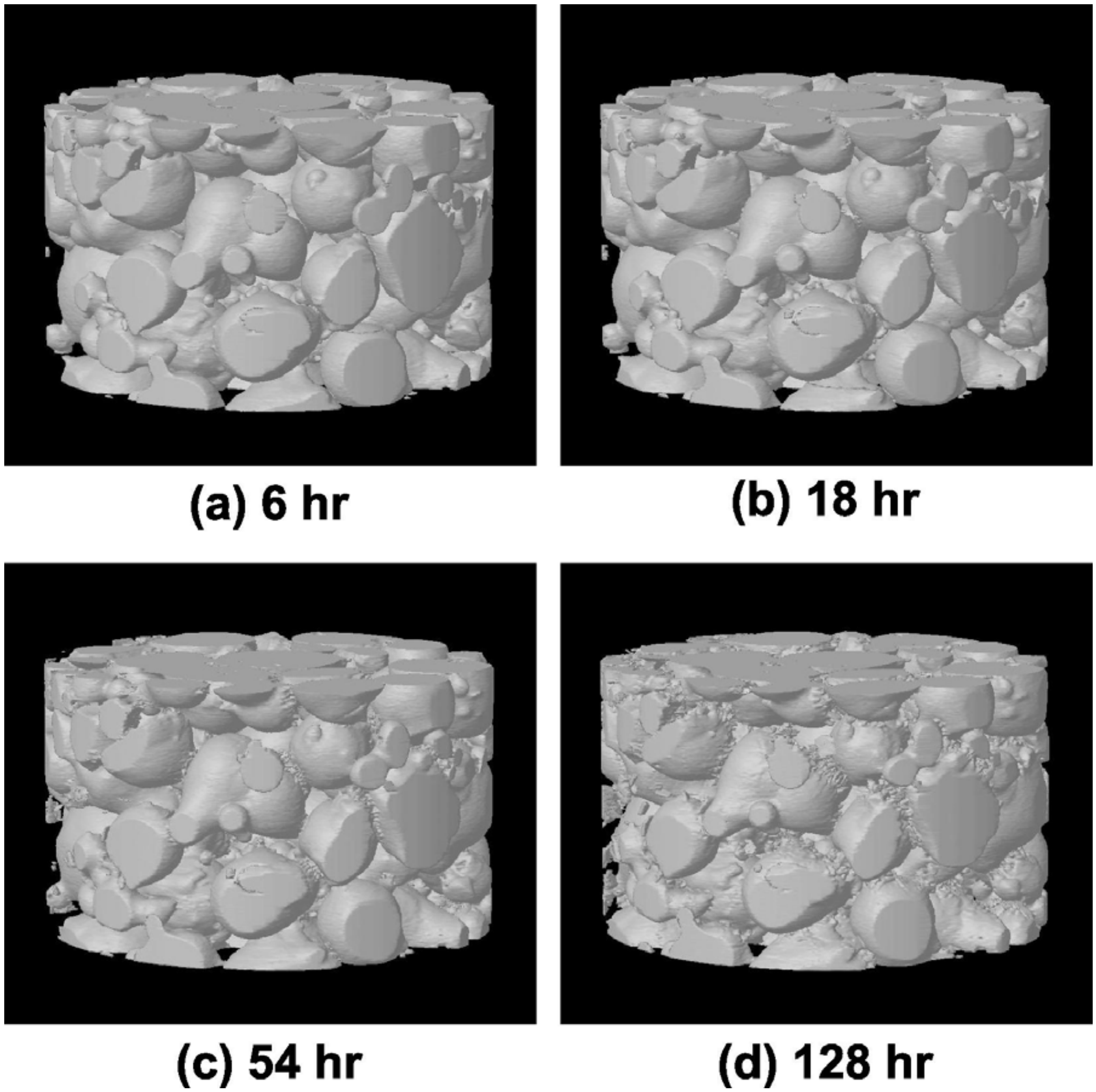


Figure 15. Selected time-series images showing the structural evolution of a 3-D ice sphere array maintained at -2.3±0.2°C over a period of 128 hours. The images were acquired using a 15 µm image pixel size.

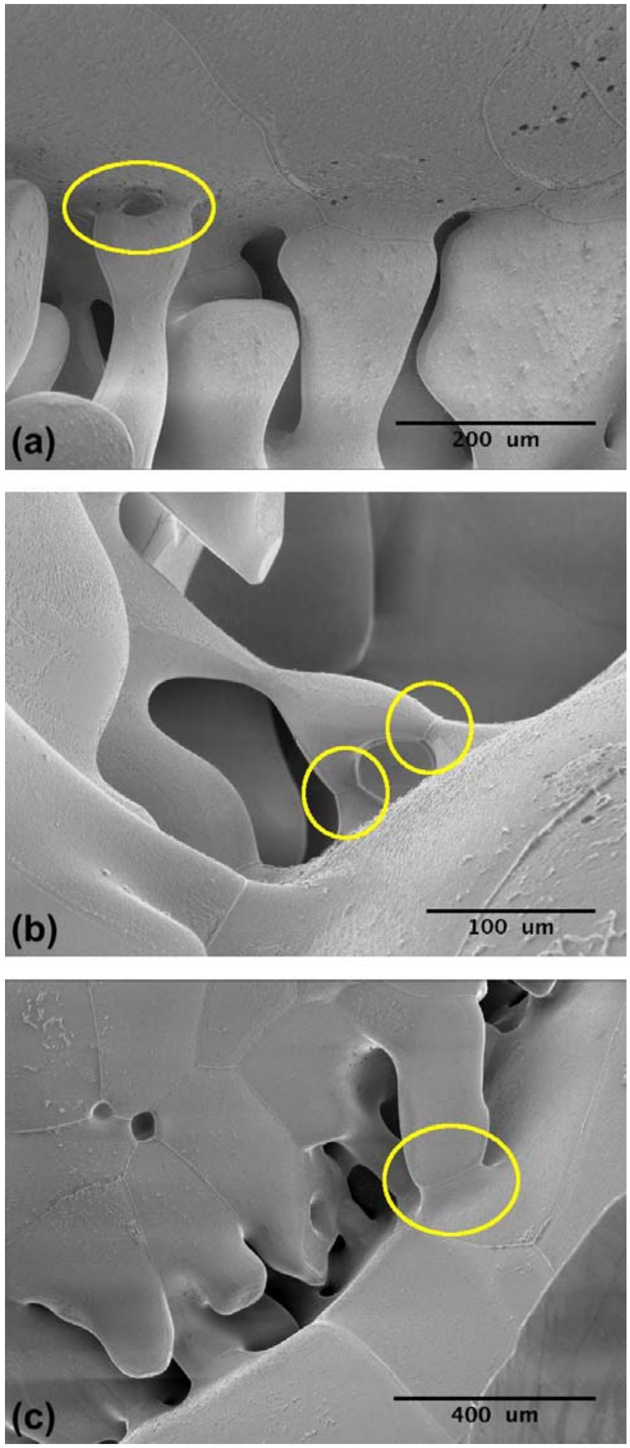


Figure 16. Secondary electron images of three necks showing mass build-ups on the surface of ice spheres and the grain boundaries between the build-ups and the protrusions.

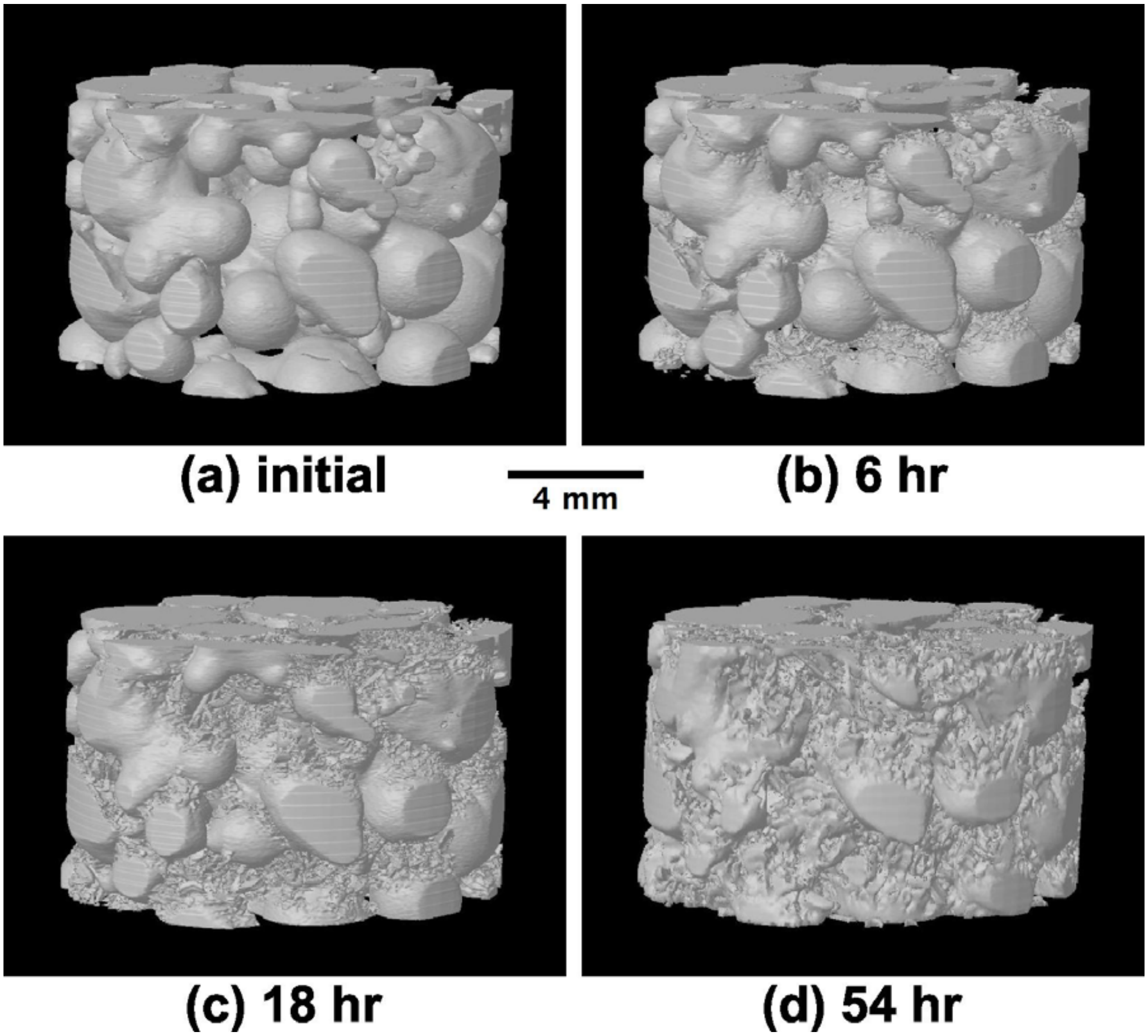


Figure 17. Selected time-series images showing the structural evolution of a 3-D ice sphere array subjected to a temperature gradient of 140°C·m^{-1} over a period of 54 hours. The images were acquired using a 15 µm image pixel size.

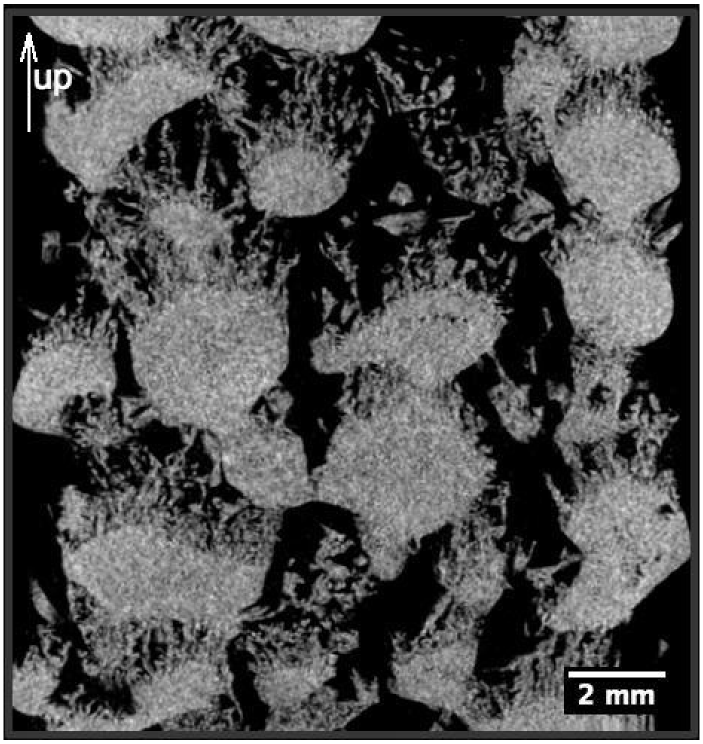


Figure 18. A gray-scale vertical cross sectional image through the 3-D ice sphere showing the development of vertical crystal alignment during the evolution under a temperature gradient of 140°C·m^{-1} over 54 hours.

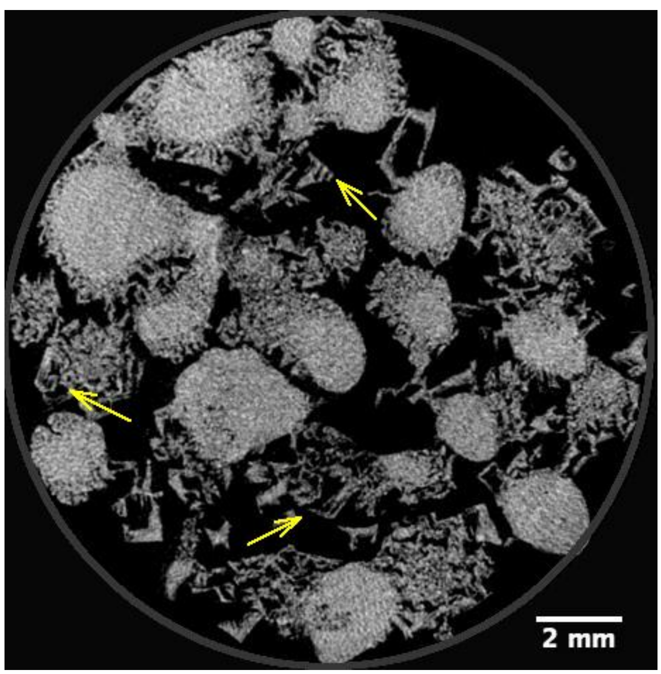


Figure 19. A gray-scale horizontal cross sectional image through the 3-D ice sphere showing the formation of depth hoar crystals during the evolution under a temperature gradient of 140°C·m^{-1} over 54 hours.

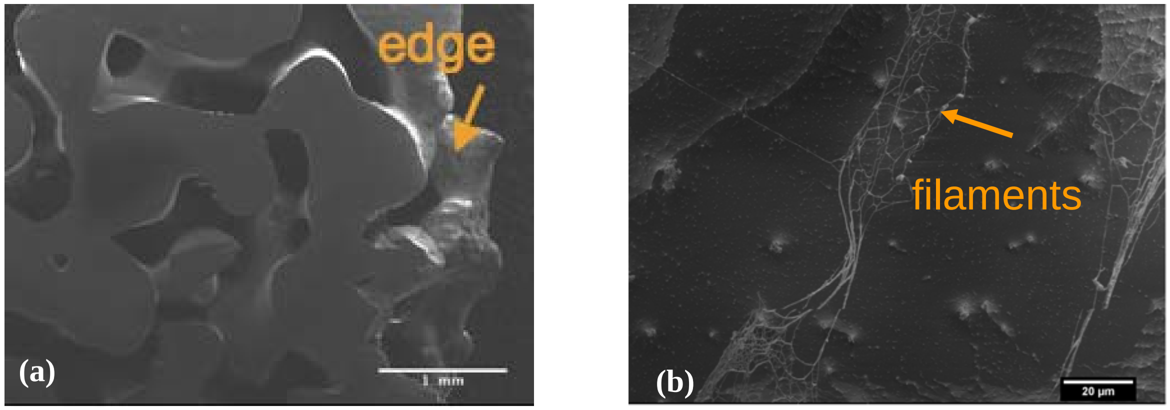


Figure 20. Secondary electron images of an Antarctic firn specimen: (a) observed at -150ºC; (b) observed at -60ºC.

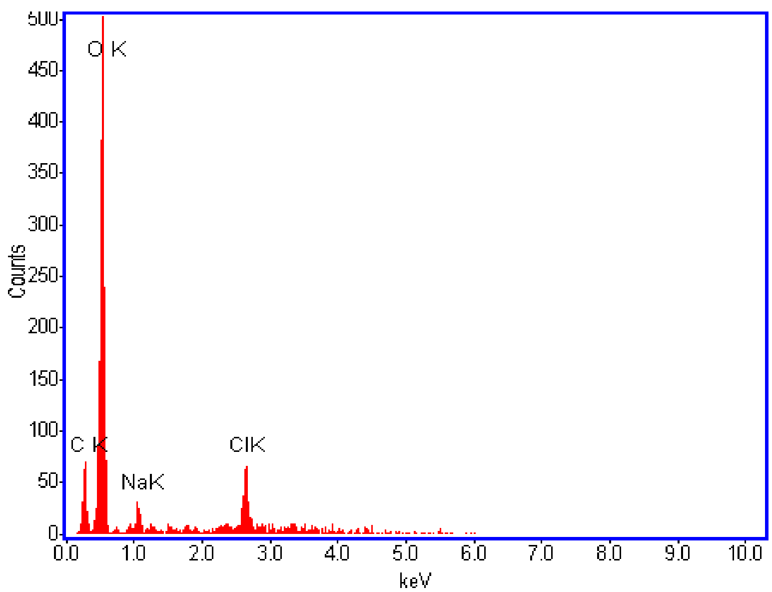


Figure 21. Energy dispersive X-ray spectrum of an etched firn specimen, showing the elements present in the filaments.

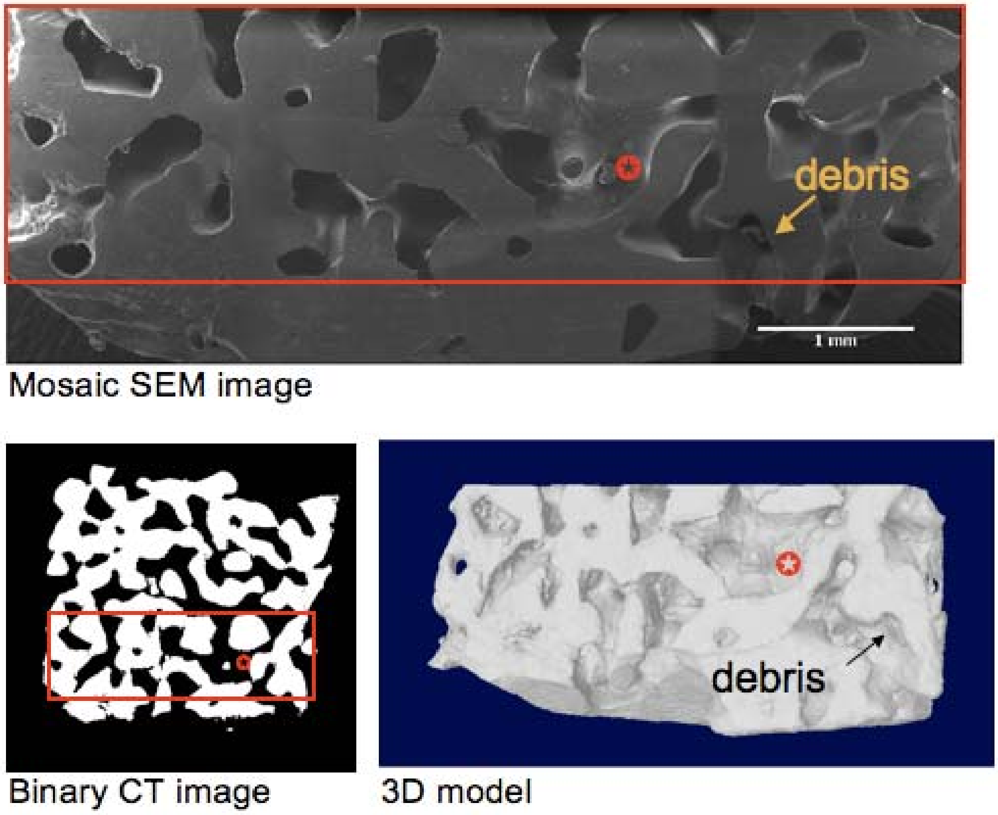


Figure 22. Combination of the images obtained using the SEM and the micro-CT. The corresponding parts are highlighted in the images. The mosaic image was constructed from a group of SEM images using ImageJ.

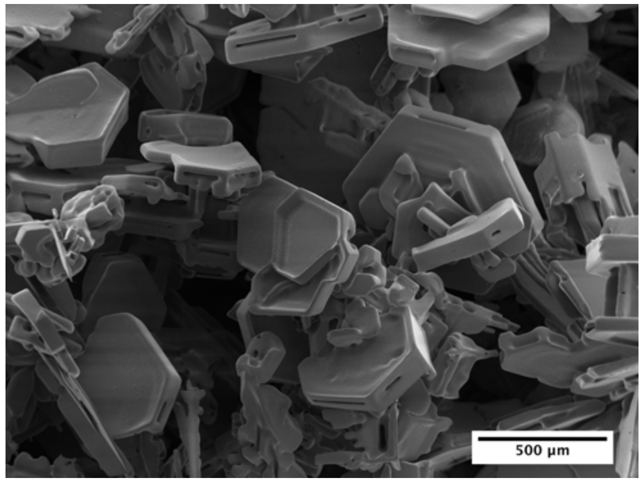


Figure 23. Secondary electron image of a fresh-snow specimen consisting of numerous snow crystals with various geometries, in which the majority are thin hexagonal plates with narrow grooves on the edges.

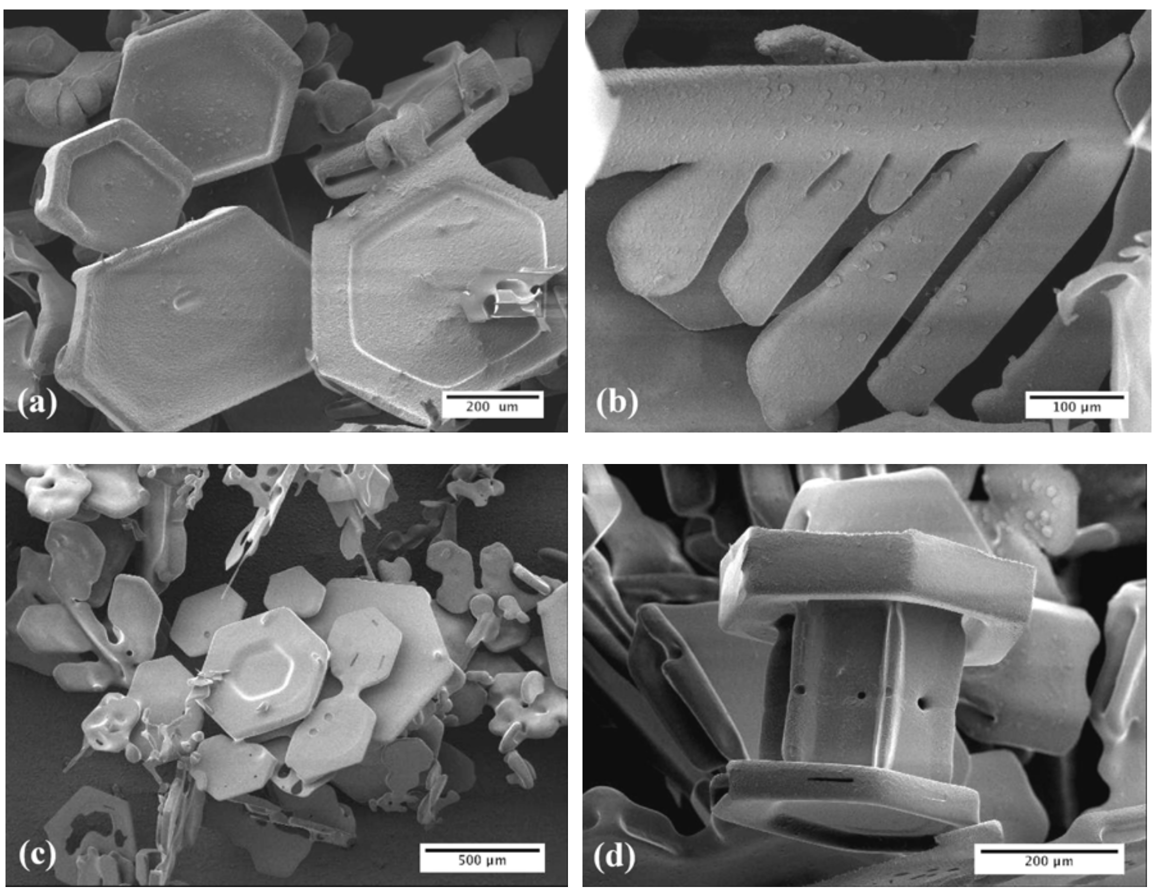
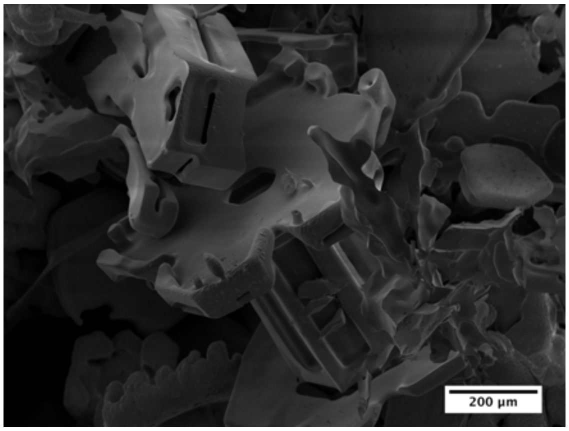
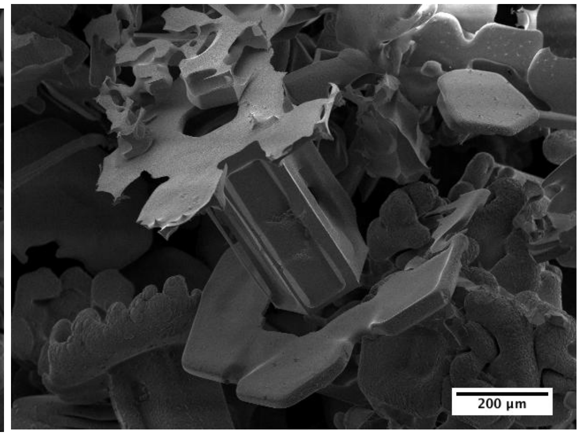


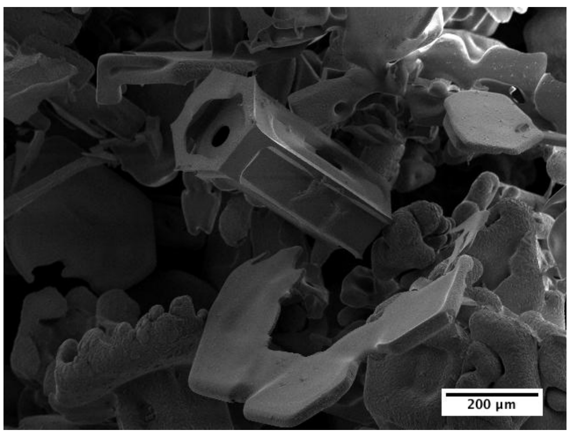
Figure 24. Secondary electron images showing the morphology of freshly-fallen snow: (a) thin hexagonal plates usually with raised edges; (b) a broken dendrite arm; (c) sectored hexagonal plates; (c) a hexagonal prism caped with a plate on each end.



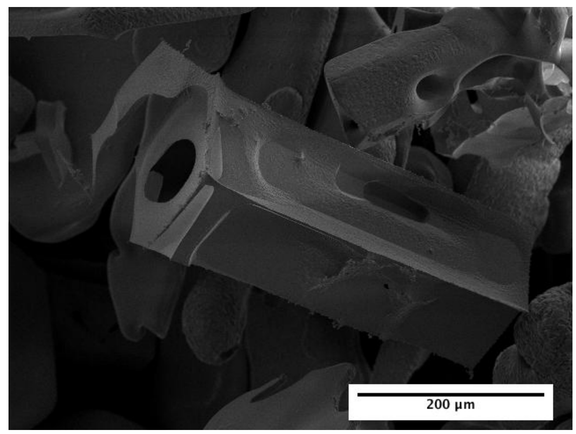
(a) T = -180°C, t = 0 min



(b) T = -150°C, t = 12 min



(c) T = -130°C, t = 20 min



(d) T = -100°C, t = 25 min

Figure 25. Secondary electron images showing the sublimation-induced structural changes of a snow crystal under high-vacuum conditions in the SEM chamber. The temperature was raised up from -180°C to -100°C over 25 minutes. The accelerating voltage was 2 kV.

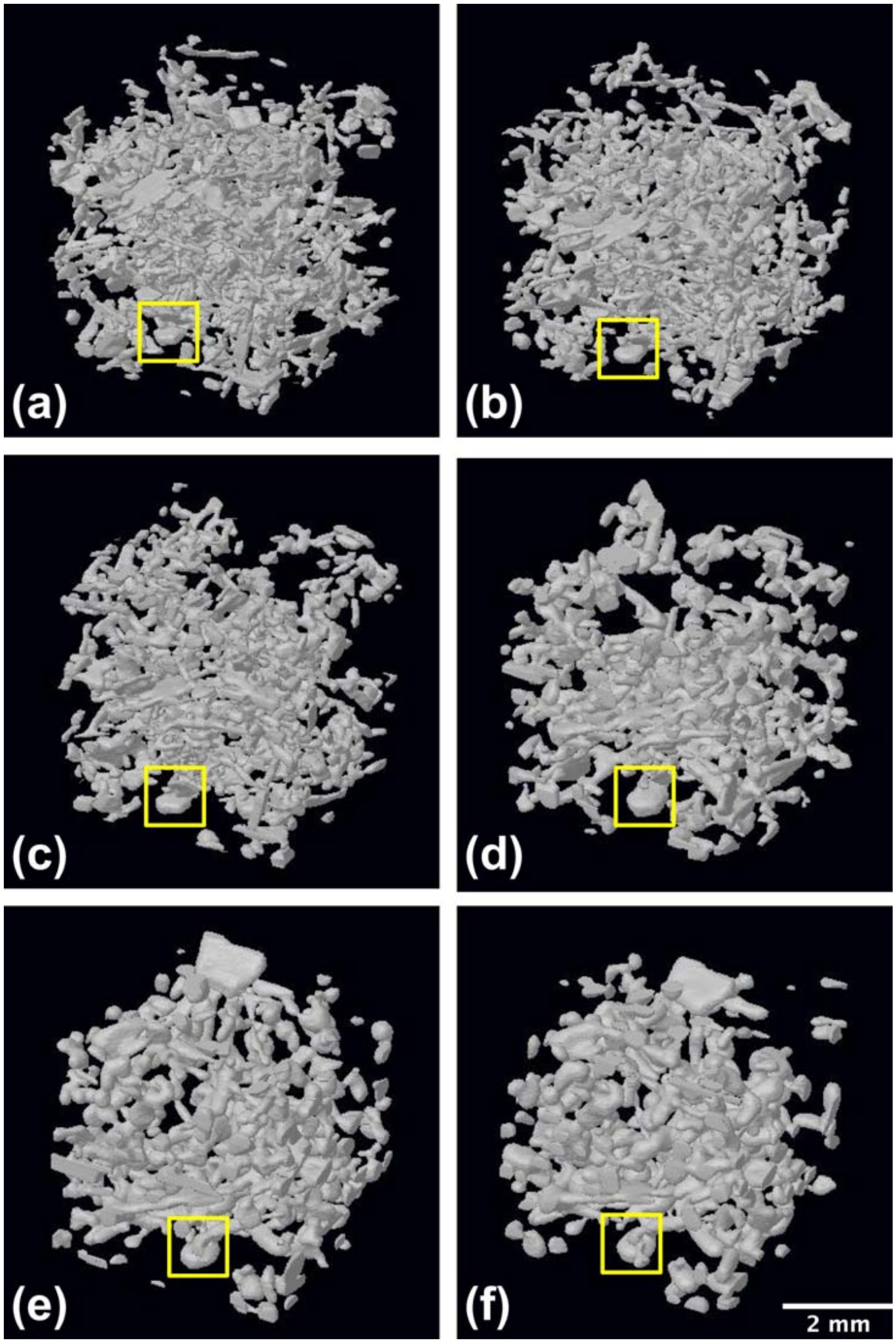


Figure 26. 3-D time-series micro-CT images showing the structural evolution of a $4 \times 4 \times 4$ mm^3 cubic volume of interest (VOI) in a natural snow specimen over a period of 70 days: (a) the initial stage, (b) after 10 days, (c) after 20 days, (d) after 30 days, (e) after 48 days, (f) after 70 days. The boxed areas indicate the tip of a branch in the same crystal.

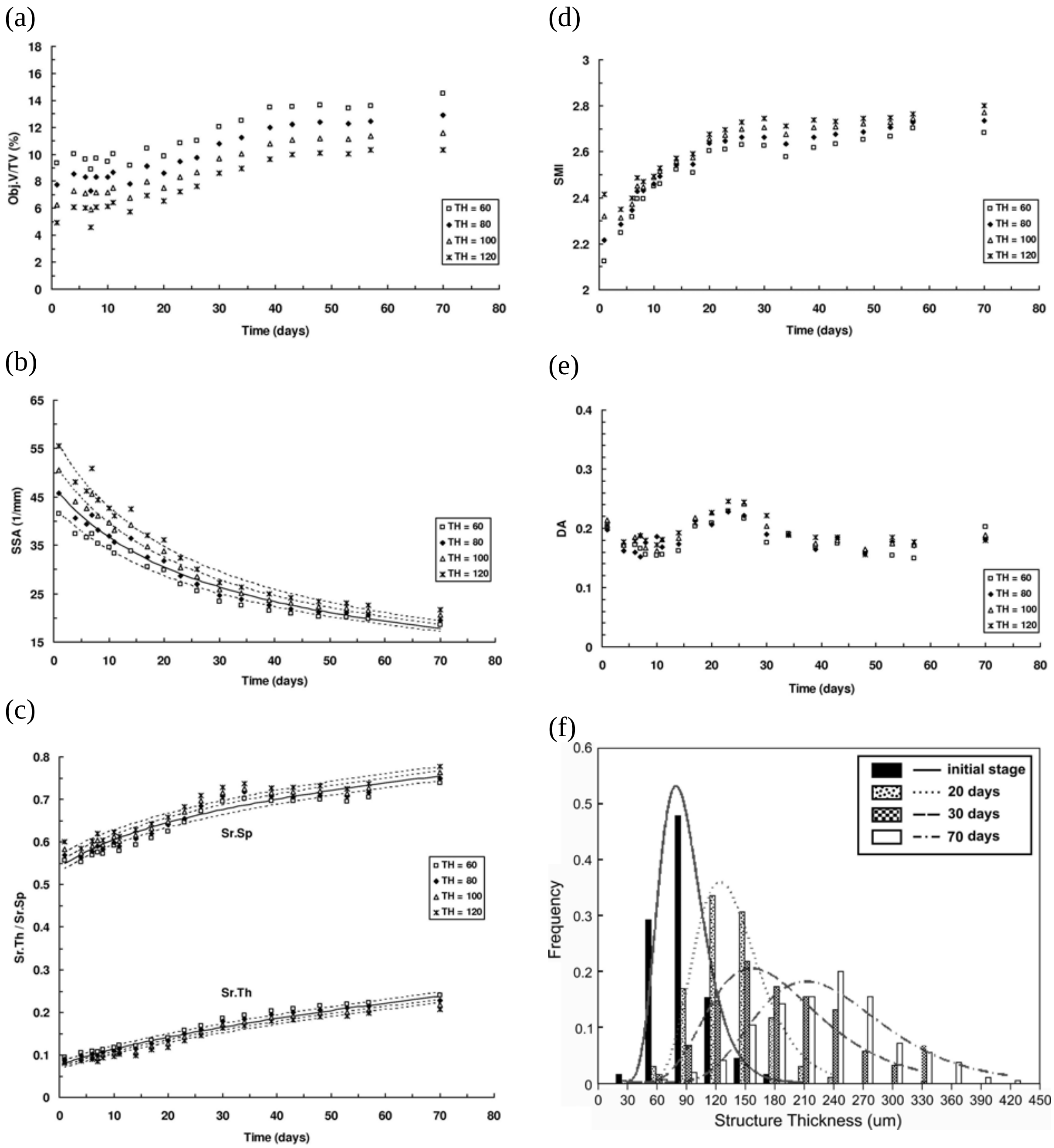


Figure 27. The evolution of structural parameters of the cubic volume shown in Figure 26: (a) relative density, (b) specific surface area, (c) structure thickness and structure separation, (d) structure model index, (e) degree of anisotropy, and (f) the distribution of local structure thickness. Four different threshold values were used for the evaluations in order to show the threshold sensitivity of the structural parameters.

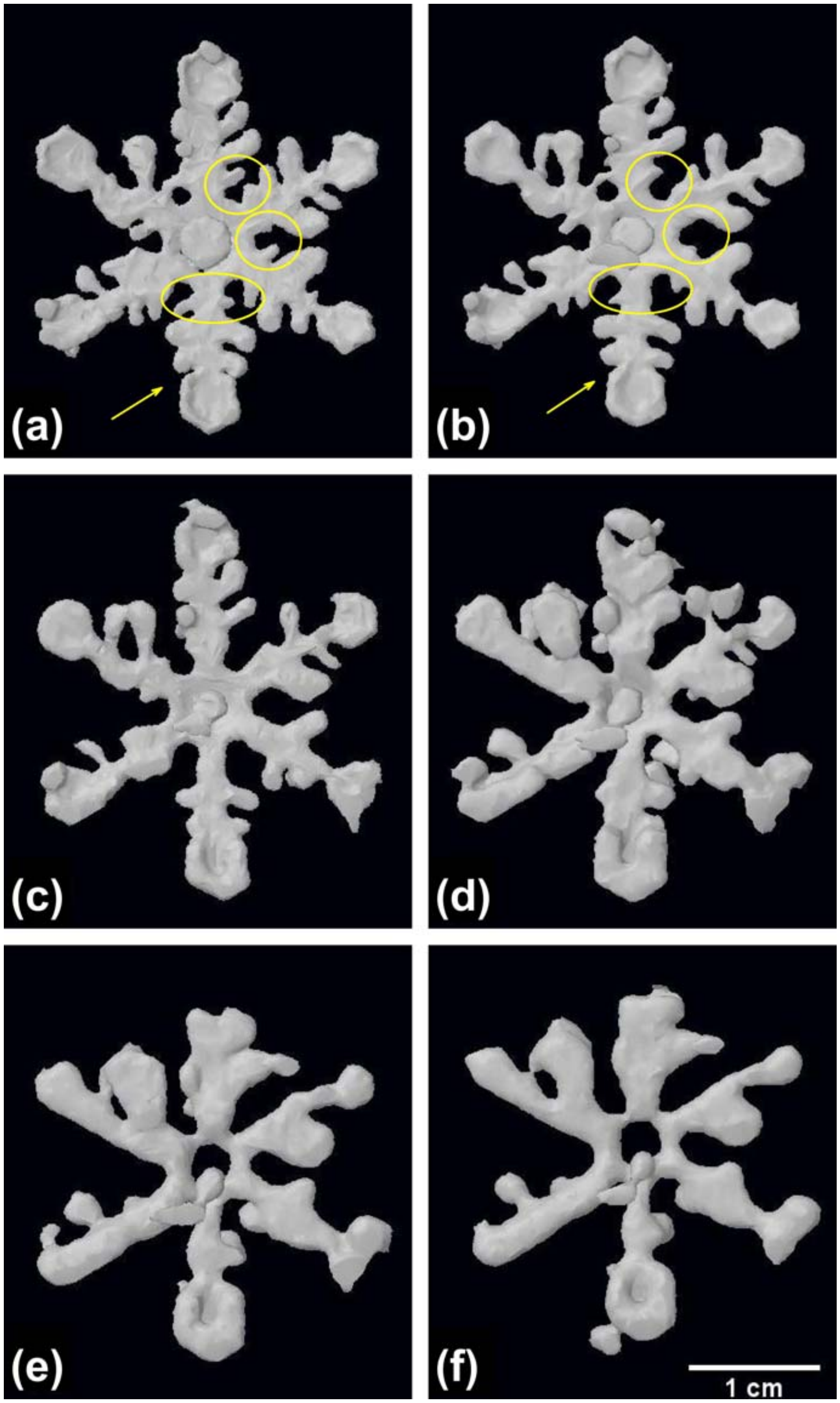


Figure 28. 3-D time-series micro-CT images extracted from the cubic VOI showing the structural evolution of an individual snow crystal over a period of 70 days: (a) the initial stage, (b) after 10 days, (c) after 20 days, (d) after 30 days, (e) after 48 days, (f) after 70 days. The circles indicate the regions where mass was lost; the arrow indicates the region where mass accumulated.

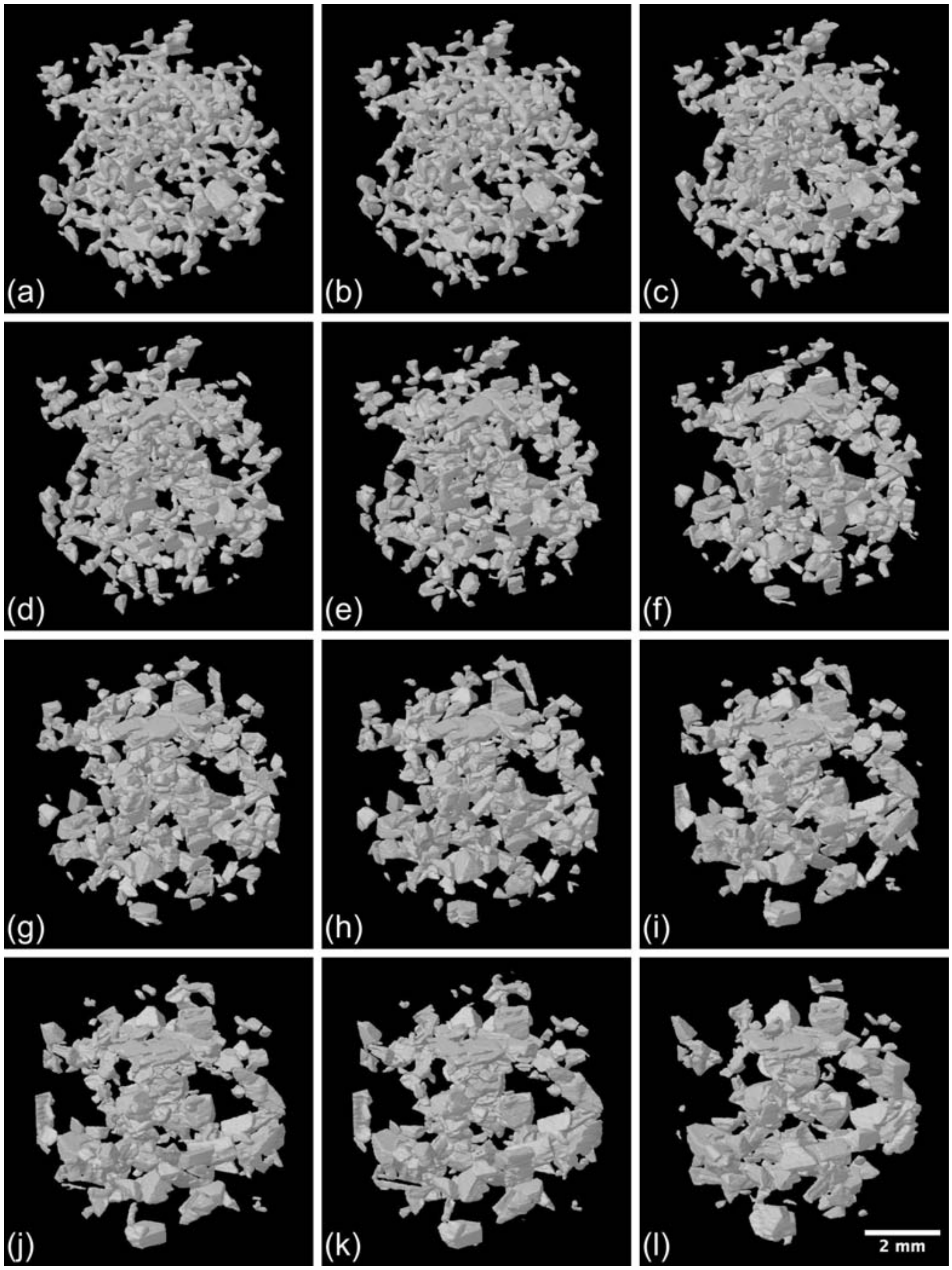


Figure 29. 3-D micro-CT images showing the structural evolution of a 4x4x4 mm^3 cubic VOI of natural snow subjected to a temperature gradient of ~50°C·m^{-1}, cooler on the bottom than the top, for a 84-hour period: (a) the initial stage; (b) after 2 hours; (c) after 14 hours; (d) after 18 hours; (e) after 24 hours; (f) after 36 hours; (g) after 42 hours; (h) after 48 hours; (i) after 60 hours; (j) after 66 hours; (k) after 72 hours; (l) after 84 hours. The images were acquired using a 15 m image pixel size.

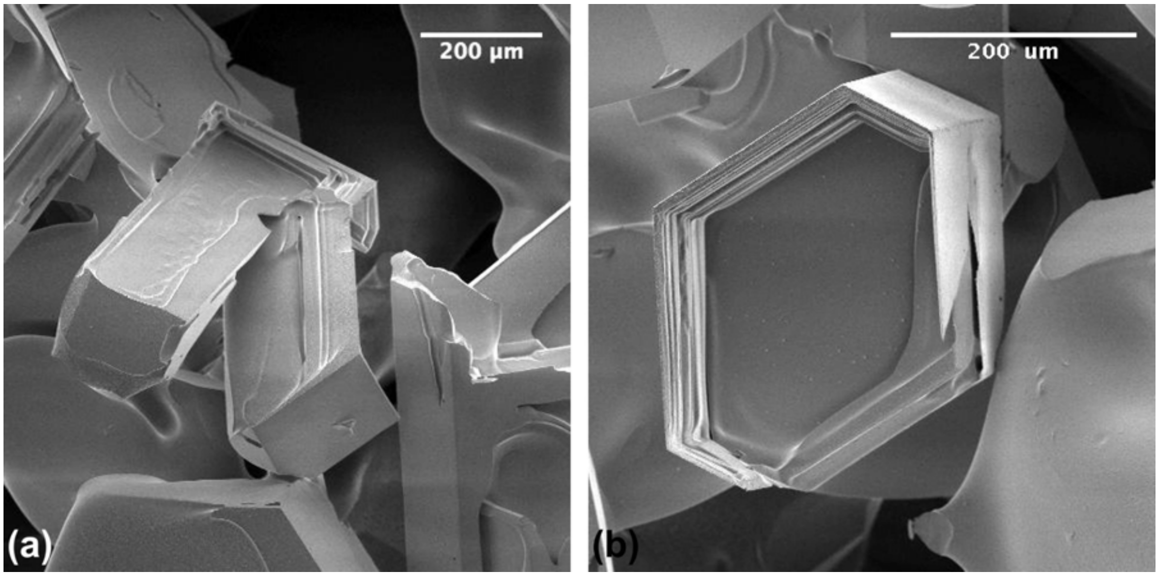


Figure 30. Secondary electron images of individual snow crystals developed under a temperature gradient showing the raised steps on the edges and the extra ice layers on the surfaces.

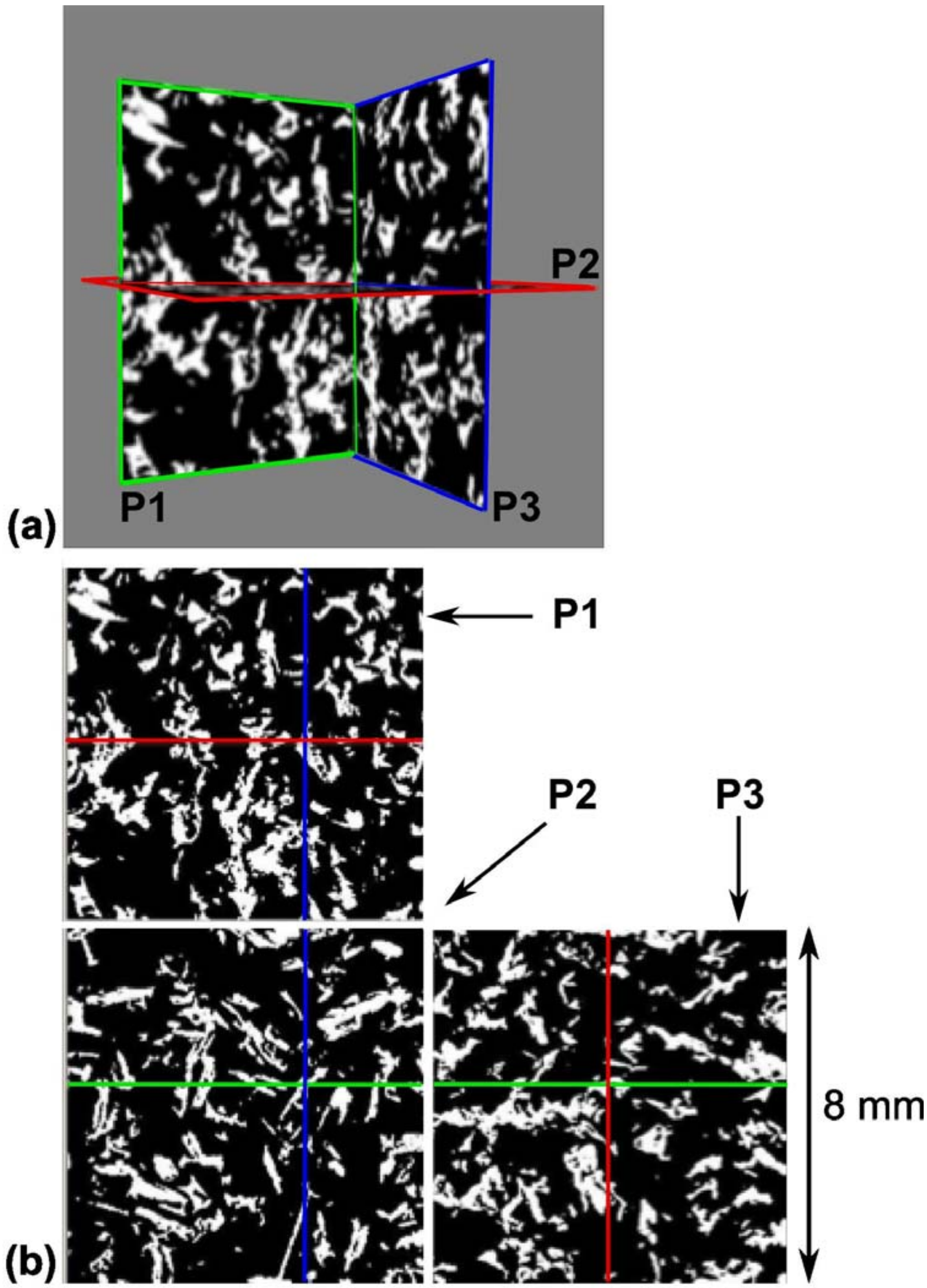


Figure 31. Cross sectional images of three orthogonal planes obtained from a snow specimen subjected to a temperature gradient of ~140°C·m^{-1} for a period of 54 hours, showing the development of vertical structural alignment: (a) a 3-D navigation view with the images of the three planes in their true positions; (b) the views of three planes.